Phenomenology and Cosmology of
(Exotic) Anomaly-Mediated SUSY Breaking Model

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1. Introduction

Original assignment:

"Exotic views in the connection between dark matter and particle physics"

$\Rightarrow$ What does "exotic" mean?

Conventional scenario (in SUSY models)

- All the SUSY particles are lighter than ~ 1 TeV
- The LSP is ($\tilde{B}$-like) neutralino, and is stable

$\Rightarrow$ The missing-E_T events will be seen at the LHC

$\Rightarrow$ Gauge coupling unification can be realized

$\Rightarrow$ Thermally produced LSP becomes dark matter

What happens if we relax (some of) these assumptions?

$\Rightarrow$ Very rich phenomenology and cosmology!

I consider an exotic type of anomaly-mediation model

- All the scalar-fermion masses are $O(10\ \text{TeV})$
- Gauginos have masses less than ~ 1 TeV
  - How can such a situation be realized?
  - What are interesting in such a scenario?

Outline

1. Introduction
2. Model
3. Phenomenology and Cosmology
4. Physics at the LHC
5. Summary

2. Model

One of the biggest issues in SUSY phenomenology:

Mediation of the SUSY breaking to the MSSM sector

Popular models have some problems

- Gravity mediation

  $\Rightarrow$ FCNC and CP problems

- Gauge mediation

  $\Rightarrow$ μ-problem

- Anomaly mediation

  $\Rightarrow$ Sequestered Kähler potential (to realize $m_{\text{MSSM}} \ll m_{3/2}$)

$\Rightarrow$ We want a simple scenario of SUSY breaking

Underlying model:

[Wells; Ibe, Moroi & Yanagida]

- SUSY is dynamically broken at a scale lower than M_{Pl}
- There is no singlet field in the SUSY breaking sector
- No special form of the Kähler potential is assumed

Soft SUSY breaking terms of MSSM fields (tree level)

$$\mathcal{L}_{\text{soft}} = \frac{c}{M_{\text{Pl}}^2} \int d^4\theta \hat{X}^\dagger \hat{X} \hat{Q}^\dagger \hat{Q} + \frac{c'}{M_{\text{Pl}}^2} \int d^2\theta \hat{\bar{X}} \hat{X} \mathcal{W}^\alpha \mathcal{W}_\alpha + \cdots$$

$$= \frac{c\langle F_X^\dagger F_X \rangle}{M_{\text{Pl}}^2} \tilde{Q}^\dagger \tilde{Q} + \frac{c'\langle \bar{X} F_X \rangle}{M_{\text{Pl}}^2} \lambda\lambda + \cdots$$

X: Fields in SUSY breaking sector ($\langle X \rangle \ll M_{\text{Pl}}$)

Q: Fields in the MSSM sector

Tree-level gaugino masses are suppressed

- Scalar masses are from (tree-level) Kähler interaction
- Gaugino masses are mainly from Anomaly-mediation
  [Randall & Sundrum; Giudice, Luty, Murayama & Rattazzi]

Mass spectrum is like (mild) split-SUSY

[Arkani-Hamed & Dimopoulos]

$\Rightarrow$ Gravitino mass: $\sim \dfrac{F_X}{M_{\text{Pl}}} \sim O(10\ \text{TeV})$

$\Rightarrow$ Scalar masses: $\sim \dfrac{F_X}{M_{\text{Pl}}} \sim O(10\ \text{TeV})$

$\Rightarrow$ Gaugino masses: $\sim \dfrac{\alpha_i}{4\pi}\dfrac{F_X}{M_{\text{Pl}}} \sim O(100\ \text{GeV})$

μ and B are $O(m_{3/2})$ via Giudice-Masiero mechanism

$$K = c_1 H_u H_d + \frac{c_2}{M_{\mathsf{Pl}}^2} X^\dagger X H_u H_d + \cdots$$

$$\Rightarrow \quad \mu = c_1 m_{3/2}, \qquad B\mu = c_1 m_{3/2}^2 + c_2 \frac{|F_X|^2}{M_{\mathsf{Pl}}^2}$$

Phenomenological implications:

- We may have to give up explaining the naturalness

  $\Rightarrow$ The landscape scenario might solve the problem

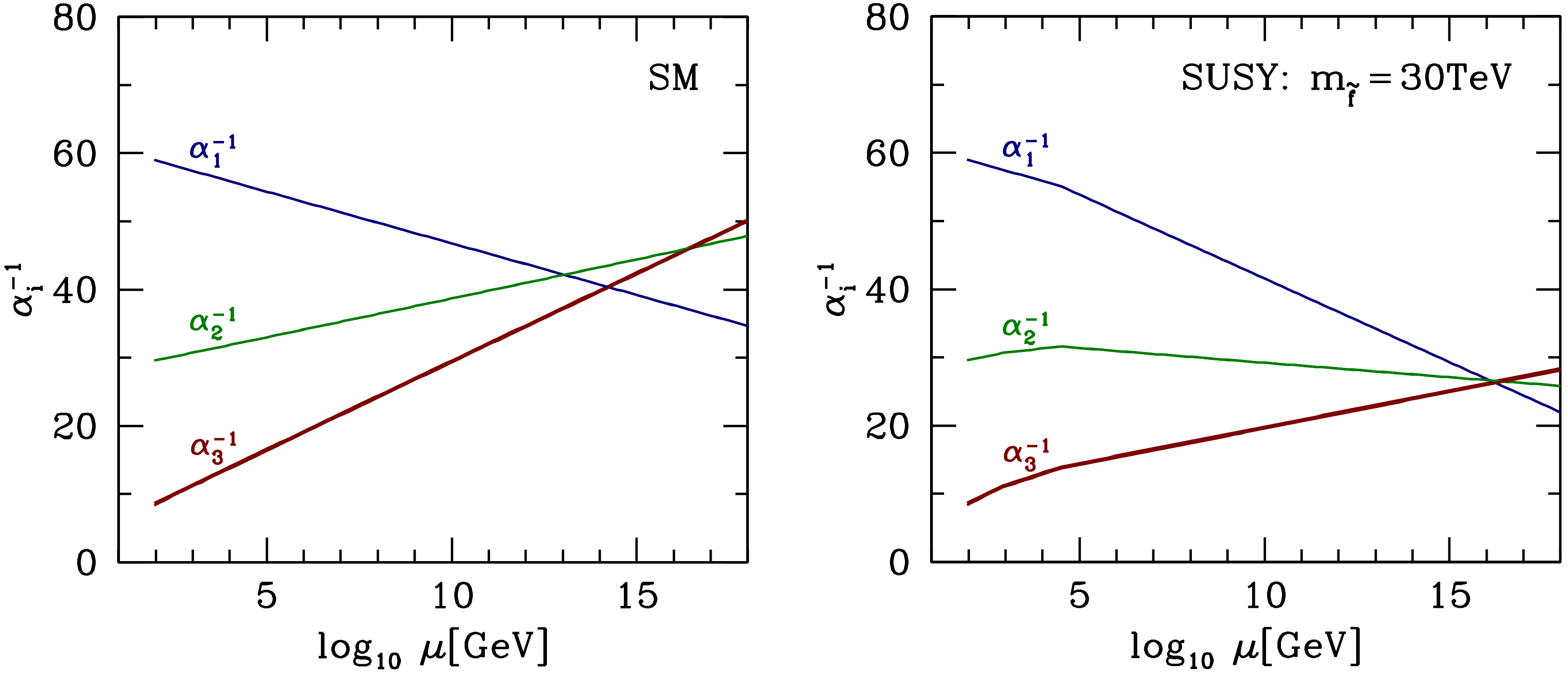
  [Arkani-Hamed & Dimopoulos]

- Model is simple
- FCNC and CP constraints are relaxed
- Interesting phenomenology and cosmology

3. Phenomenology and Cosmology

Gauge-coupling unification

[See also Giudice & Romanino]

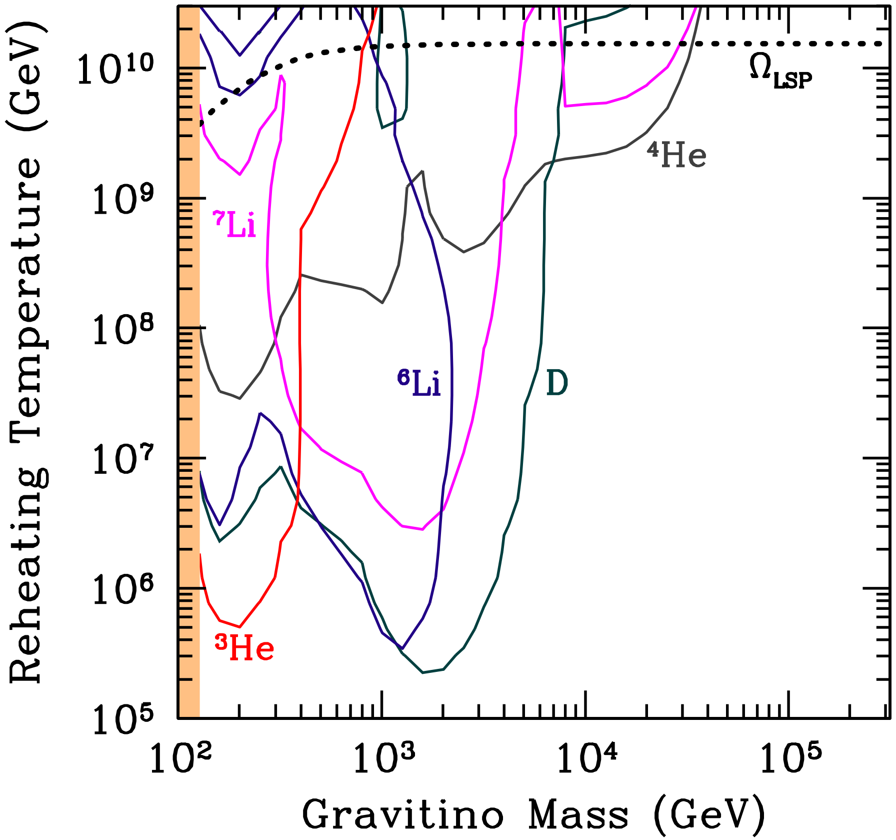


- Coupling unification is still possible
- Proton-decay constraints are relaxed

  $\Rightarrow \tau_p$ is long enough if $\tan\beta \lesssim 10$ (with $UUDE$-operator)

Cosmology: BBN constraints on the reheating temperature

[See, for example, Kawasaki, Kohri, Moroi & Yotsuyanagi]



T_R : Reheating temperature

$$\frac{n_{3/2}}{n_\gamma} \simeq 1.6 \times 10^{-11} \times \left(\frac{T_R}{10^{10}\ \text{GeV}}\right)$$

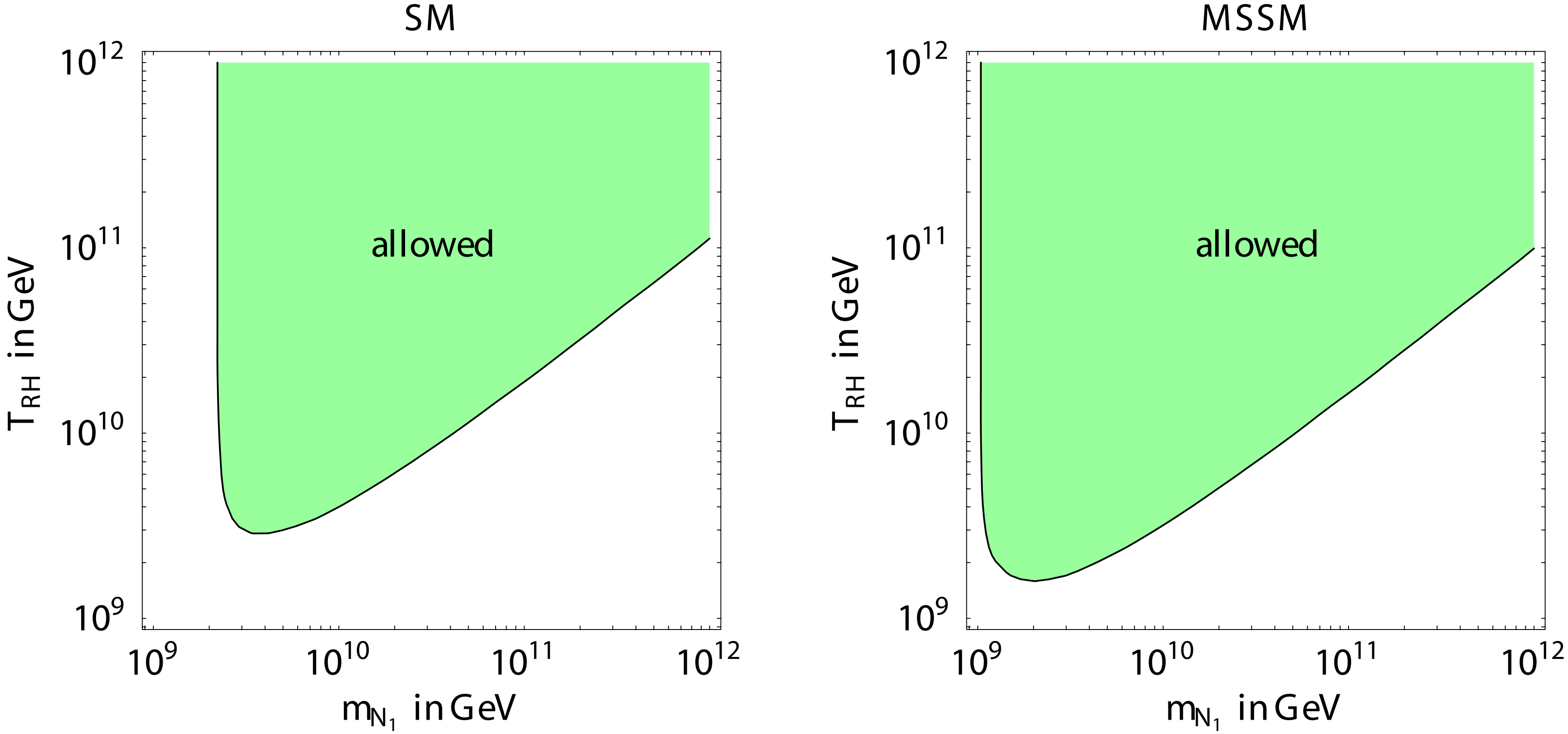
$$\tau_{3/2} \simeq 0.014\ \text{sec} \times \left(\frac{m_{3/2}}{100\ \text{TeV}}\right)^{-3}$$

- $T_R \sim 10^{9-10}$ GeV is possible if $m_{3/2} \sim O(10\ \text{TeV})$
- $T_R \lesssim 10^{5-6}$ GeV, if $m_{3/2} \lesssim 1$ TeV

One implication: Thermal leptogenesis becomes possible

For thermal leptogenesis, $T_{\rm R} \gtrsim 10^{9-10}$ GeV is necessary

[Buchmuller, Di Bari & Plumacher; Giudice, Notari, Raidal, Riotto & Strumia]



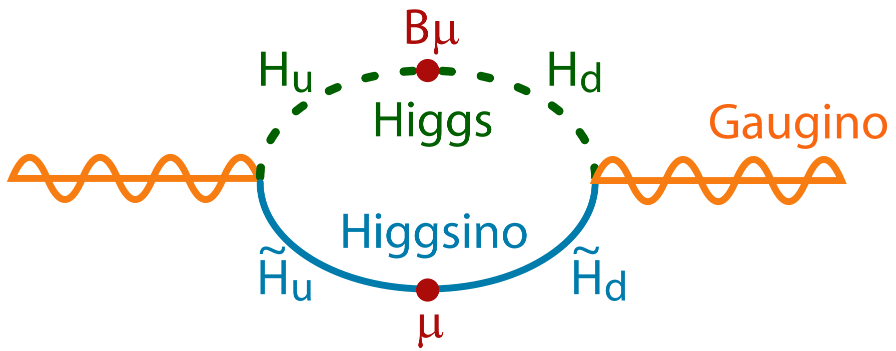
[Giudice, Notari, Raidal, Riotto & Strumia]

$\Rightarrow$ The thermal leptogenesis works if $m_{3/2} \gtrsim O(10 \text{ TeV})$

What is the LSP?

Gaugino masses: Anomaly-mediation + Higgs-Higgsino loop

[Giudice, Luty, Murayama & Rattazzi; Gherghetta, Giudice & Wells]

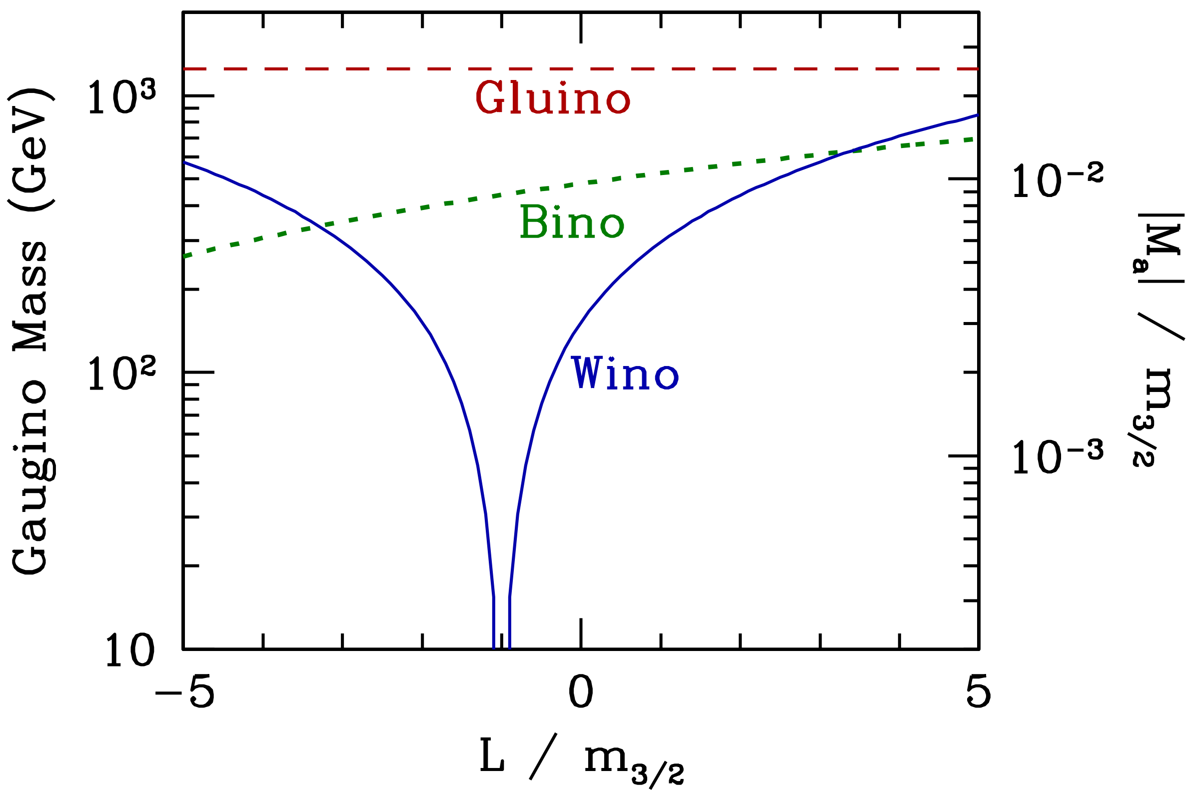


$$M_1 \simeq \frac{g_1^2}{16\pi^2}\left(11 m_{3/2} + L\right) \qquad L \equiv \mu \sin 2\beta \frac{m_A^2}{|\mu|^2 - m_A^2} \ln \frac{|\mu|^2}{m_A^2}$$

$$M_2 \simeq \frac{g_2^2}{16\pi^2}\left(m_{3/2} + L\right)$$

$$M_3 \simeq \frac{g_3^2}{16\pi^2}\left(-3 m_{3/2}\right)$$

Gaugino masses for Arg$(L/m_{3/2}) = 0$ (with $m_{3/2} = 50$ TeV)



⇒ Gaugino masses deviate from pure-AMSB relation

⇒ Wino is the lightest gaugino when $|L| \lesssim 3|m_{3/2}|$

It is likely that $m_{\tilde{W}} < m_{\tilde{B}}$, $m_{\tilde{g}}$

$\Rightarrow$ Hereafter, I assume that the Wino is the lightest gaugino

Then, the neutral Wino $\tilde{W}^0$ becomes the LSP

- $m_{\tilde{W}^\pm} - m_{\tilde{W}^0} \simeq 155 - 170$ MeV (by radiative correction)
- $\tilde{W}^\pm$ decays into $\tilde{W}^0$ and soft $\pi^\pm$
- Lifetime of $\tilde{W}^\pm$: $c\tau_{\tilde{W}^\pm \to \tilde{W}^0 \pi^\pm} \sim 5$ cm

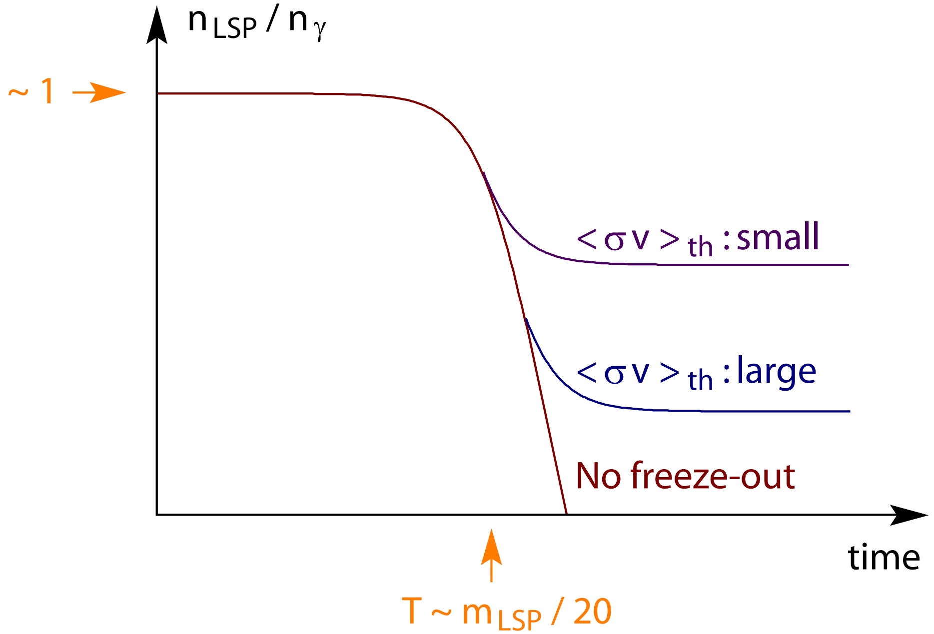
Gaugino masses depend on $|m_{3/2}|$, $|L|$ and Arg$(L/m_{3/2})$

$$\left| \frac{10 g_1^2}{3 g_3^2} m_{\tilde{g}} - \frac{g_1^2}{g_2^2} m_{\tilde{W}} \right| \lesssim m_{\tilde{B}} \lesssim \frac{10 g_1^2}{3 g_3^2} m_{\tilde{g}} + \frac{g_1^2}{g_2^2} m_{\tilde{W}}$$

Dark matter

$\tilde{W}^0$ has sizable annihilation cross section

$$\langle \sigma v \rangle_{\tilde{W}^0 \tilde{W}^0 \to W^+ W^-} \simeq \frac{g_2^4}{2\pi} \frac{1}{m_{\tilde{W}}^2} \times \left[1 + O(m_W^2 / m_{\tilde{W}}^2)\right] \Leftarrow s\text{-wave}$$



$$\Rightarrow \quad \Omega_{\mathrm{LSP}}^{(\mathrm{thermal})} \simeq 0.2 \times \left(\frac{\langle \sigma v \rangle}{0.9 \text{ pb}} \right)^{-1}$$

$$\Rightarrow \Omega_{\tilde{W}^0}^{(\mathrm{thermal})} \ll \Omega_{\mathrm{DM}}, \text{ if } m_{\tilde{W}^0} \lesssim 2 \text{ TeV}$$

Wino in the present universe may have non-thermal origin

1. An "exotic" particle is somehow produced in the early universe
2. It decays into $\tilde{W}^0$ at the temperature below the freeze-out temperature of $\tilde{W}^0$

Candidates for the "exotic" particle

- Gravitino

  [Kawasaki & Moroi; Gherghetta, Giudice & Wells]

- Cosmological moduli fields (particle, or condensation)

  [Moroi & Randall]

- $\cdots$

Wino-LSP production via the gravitino decay

1. Gravitino is produced after inflation
2. Gravitino decays in the late universe

$$\Omega_{\tilde{W}^0} \simeq 0.13 \times \left(\frac{m_{\tilde{W}}}{100 \text{ GeV}} \right) \left(\frac{T_{\mathrm{R}}}{10^{10} \text{ GeV}} \right)$$

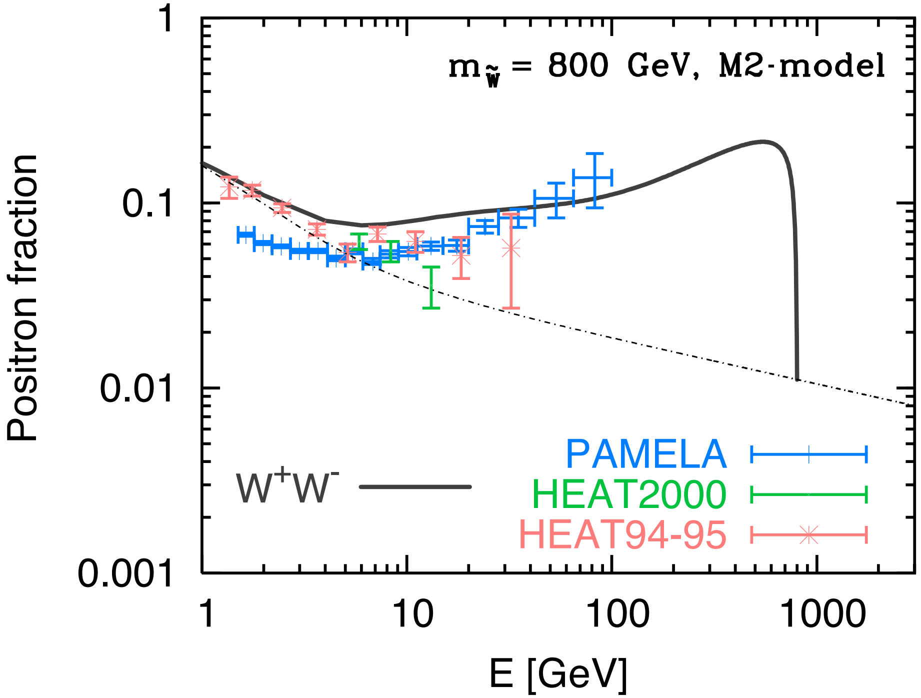
$\tilde{W}^0$ can be dark matter if $T_{\mathrm{R}} \sim 10^{10}$ GeV and $m_{3/2} \sim O(10 \text{ TeV})$

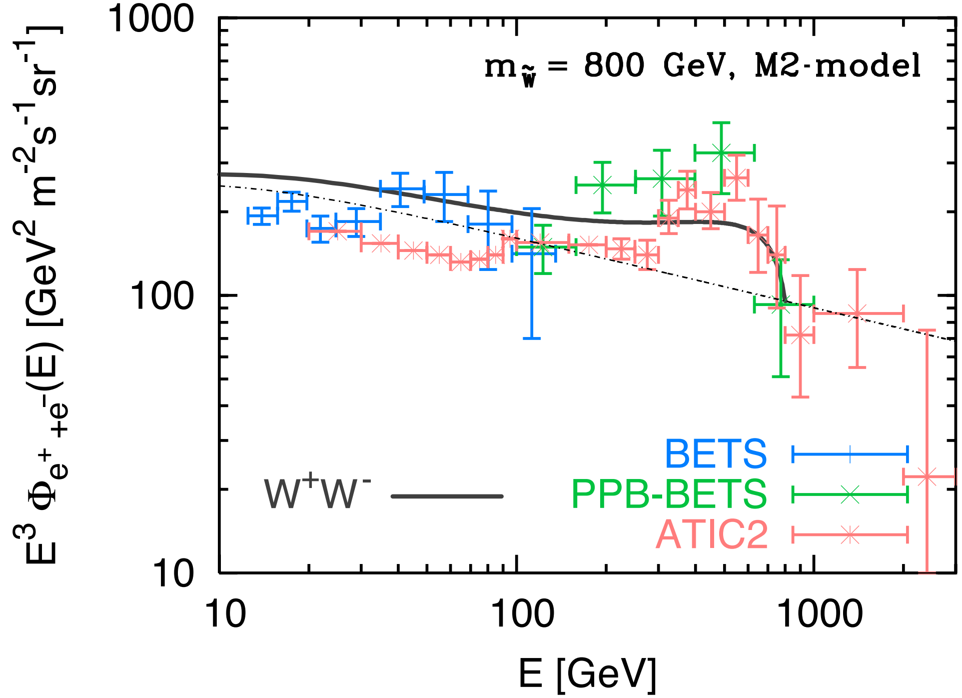
- The BBN constraints can be avoided
- Thermal leptogenesis works

Annihilation of $\tilde{W}^0$-CDM produces cosmic-ray $e^{\pm}$

$\Rightarrow$ A solution to the PAMELA / ATIC anomalies?

[Cirelli, Kadastik, Raidal & Strumia; Grajek et al.]





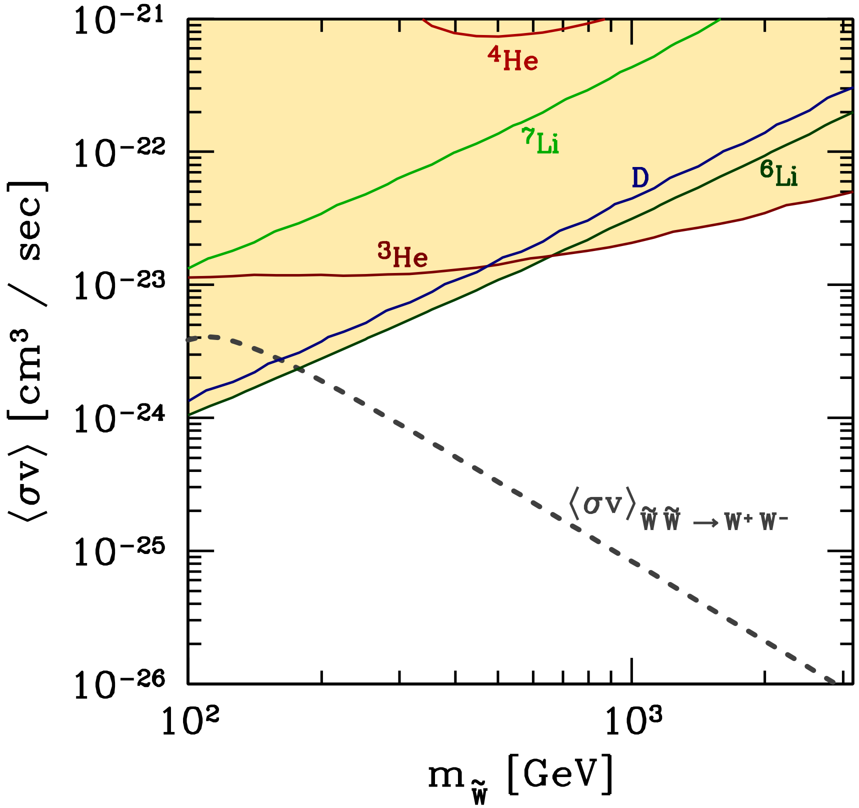
$\bar{p}$ is also produced, which gives a stringent constraint

$\Rightarrow$ However, $\bar{p}$-flux is sensitive to the propagation model

$\tilde{W}^0$ also annihilates during the BBN epoch

[Jedamzik; Hisano, Kawasaki, Kohri, Moroi & Nakayama]

Annihilation rate: $n_{\tilde{W}^0}\langle\sigma v\rangle \propto$ (Scale factor)$^{-3}$



$\Omega_{\tilde{W}^0} = \Omega_{\rm DM}$ is used

$\Rightarrow$ Lower bound on $m_{\tilde{W}}$: $m_{\tilde{W}} \gtrsim 200$ GeV

4. Physics at the LHC (MC Analysis)

Only the gauginos are produced at the LHC

- Can we find SUSY signals?
- What can we measure (and learn)?

We choose: $|m_{3/2}| = 39$ TeV, $|L| = 28$ TeV, Arg$(L/m_{3/2}) = 0$

$\Rightarrow m_{\tilde{B}} = 400$ GeV, $m_{\tilde{W}} = 200$ GeV, $m_{\tilde{g}} = 1$ TeV

Dominant production process of gauginos: $pp \to \tilde{g}\tilde{g}$

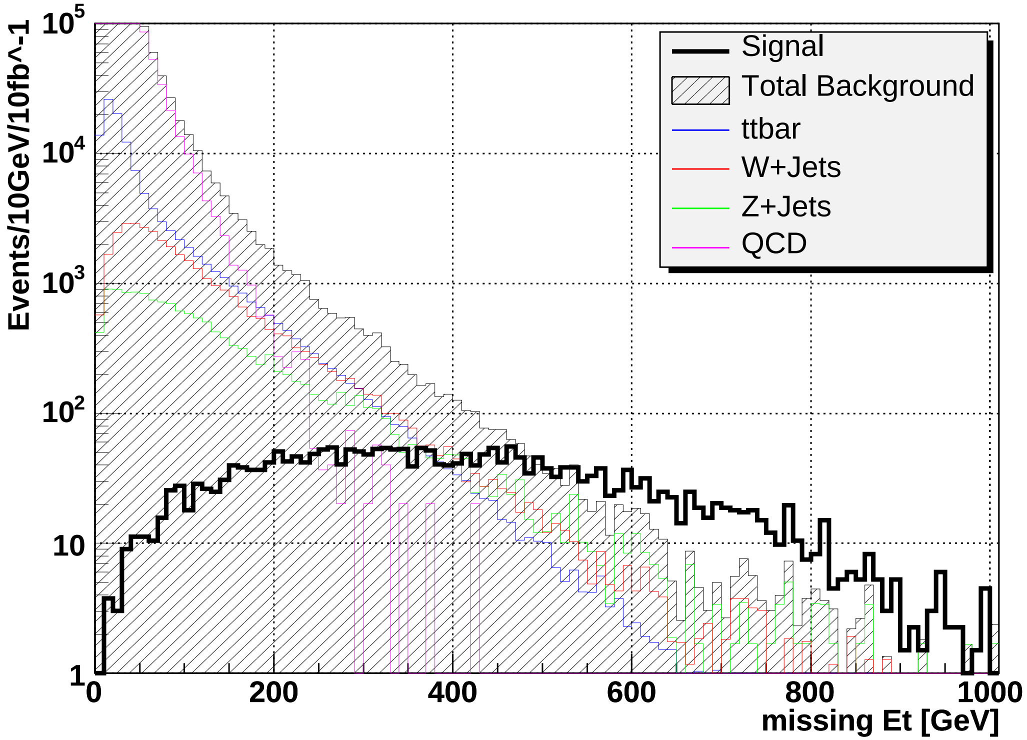
For $m_{\tilde{g}} = 1$ TeV, $\sigma_{pp\to\tilde{g}\tilde{g}} \simeq 220$ fb

Once produced, gluino decays into lighter particles

$\tilde{g} \to \tilde{W} q\bar{q}$ / $\tilde{B} q\bar{q}$ (followed by the decay of $\tilde{B}$)

Discovery of SUSY signal is easy with missing $\not{E}_T$ events

[Asai, Moroi, Nishihara & Yanagida]



- Discovery potential: $m_{\tilde{g}} \lesssim 1.2$ TeV (with $\mathcal{L} = 10$ fb^{-1})
- $m_{\tilde{g}}$ may be determined by the cross-section measurements

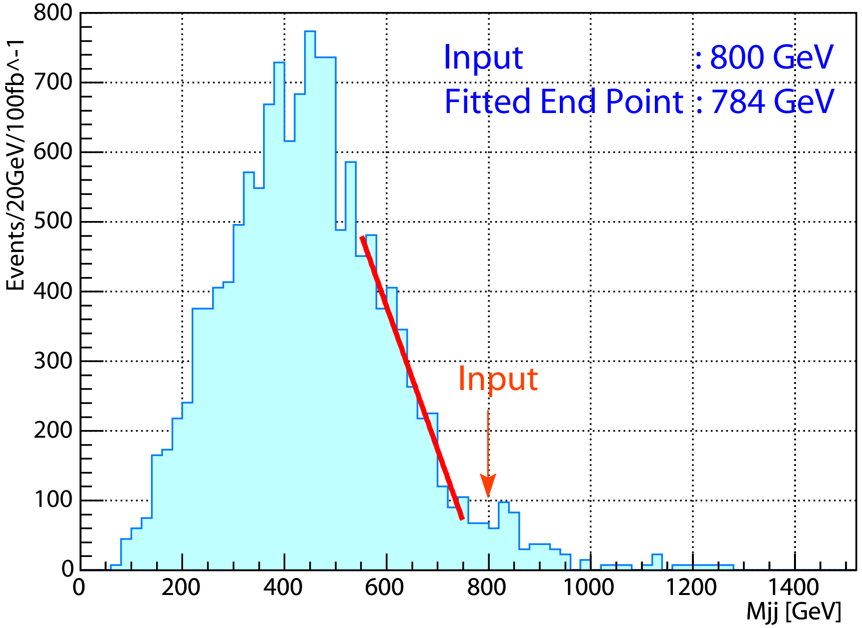
  $\Rightarrow \delta m_{\tilde{g}} \simeq 10$ %

$m_{\tilde{g}} - m_{\tilde{W}}$ can be measured from dijet invariant mass

For $\tilde{g} \to \tilde{W} q\bar{q}$: $M_{q\bar{q}} \leq m_{\tilde{g}} - m_{\tilde{W}} \Leftarrow$ parton-level relation

Dijet invariant mass ($\mathcal{L} = 100$ fb^{-1})

- Four leading jets (j_1, j_2, j_3, j_4) are used
- (M_{13}, M_{24}) or (M_{14}, M_{23}), whichever $|M_{ij} - M_{kl}|$ is smaller



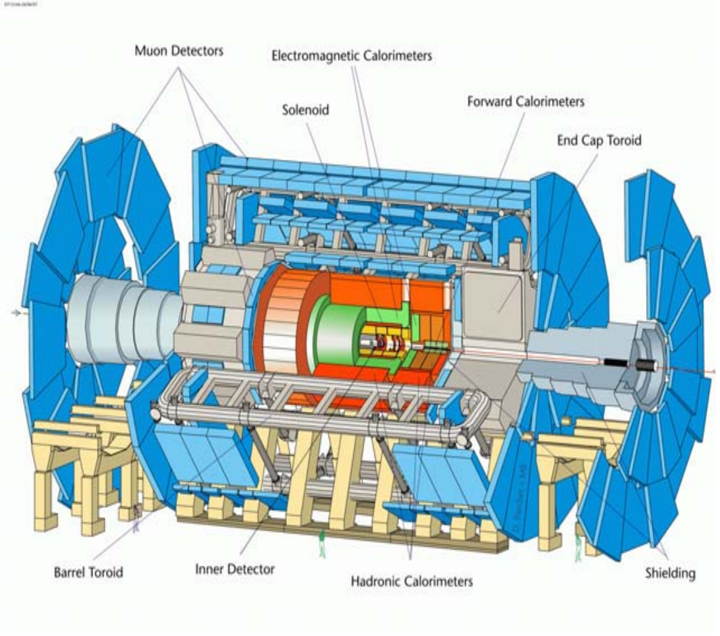
$\Rightarrow \delta(m_{\tilde{g}} - m_{\tilde{W}}) \simeq 5\ \%$

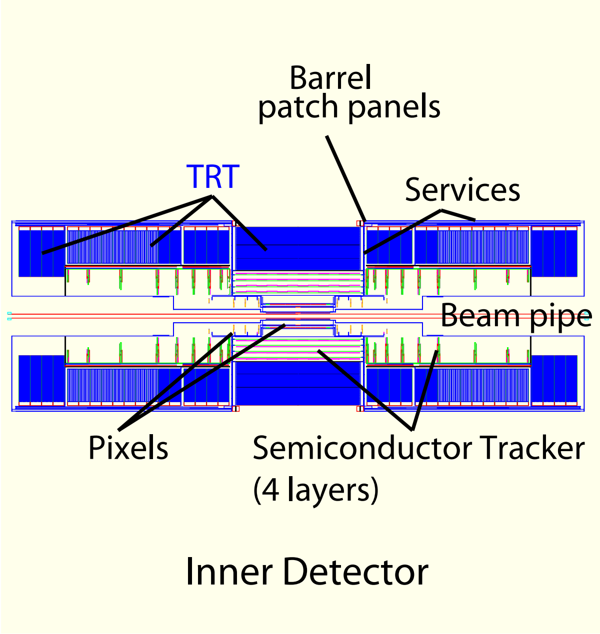
Can we find charged Wino even if $c\tau_{\tilde{W}^\pm} \sim 5$ cm?

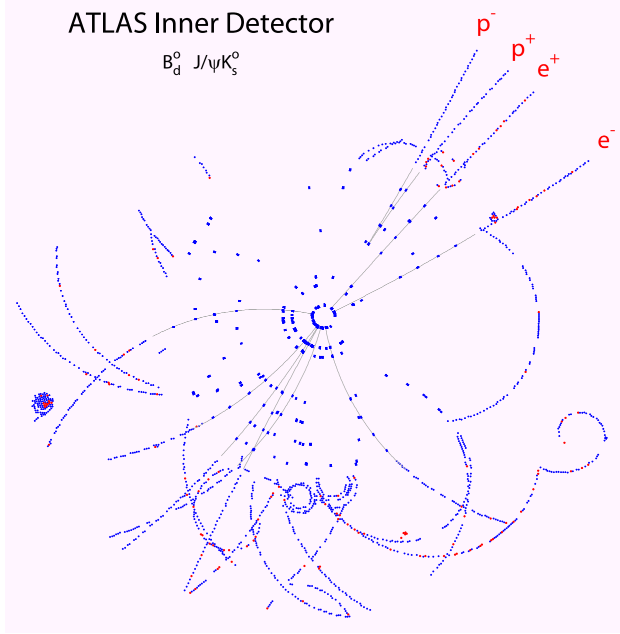
[For Tevatron, see Feng, Moroi, Randall, Strasslar & Su]

$\Rightarrow$ ATLAS (probably, also CMS) has a good tracking system

$\Rightarrow$ Central trackers can be used to find $\tilde{W}^\pm$ tracks







- TRT continuously follows charged tracks

Reconstruction of the $\tilde{W}^{\pm}$ track is possible with trackers

[Asai, Azuma, Jinnouchi, Moroi & Yanagida]

MC analysis showed that hits in the pixel and 1st + 2nd SCT layers are enough to reconstruct charged track

SCT layer	1st	2nd	3rd	4th	TRT
L_T (mm)	299	371	443	514	554

If a $\tilde{W}^{\pm}$ travels with $L_T \gtrsim 37$ cm, it can be identified

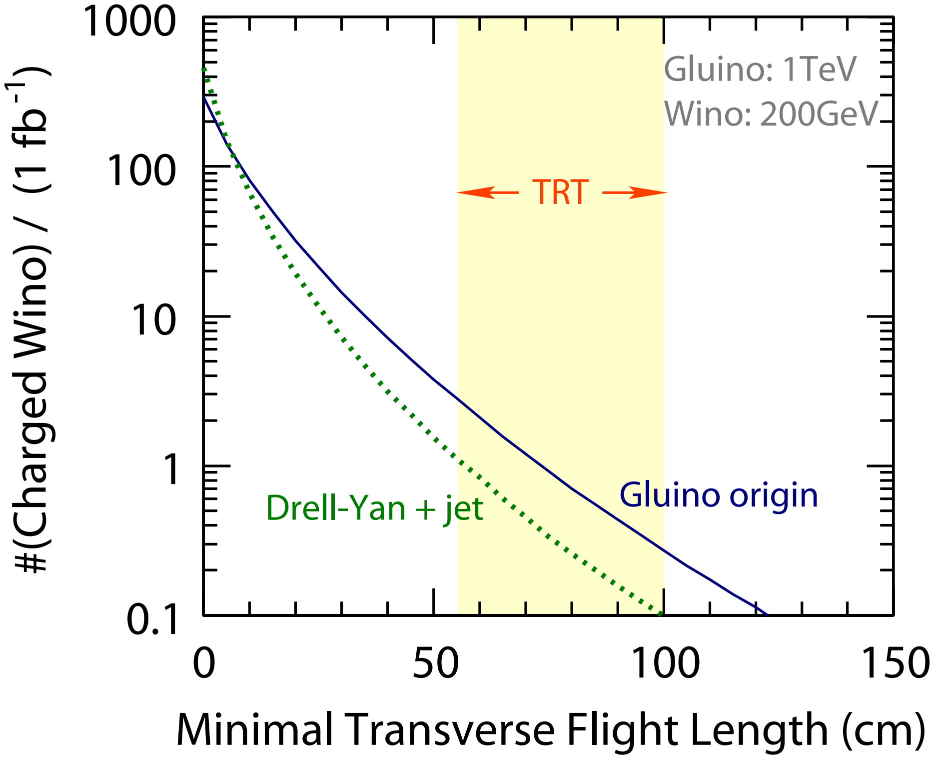
- It gives a track which disappears in the detector

  $\Rightarrow$ Very exotic

- Its momentum can be determined

  $\Rightarrow$ It can be used for event reconstruction

Cross section to produce $\tilde{W}^{\pm}$-tracks with some length



$c\tau_{\tilde{W}^{\pm}} = 5.1$ cm

⇒ Sizable amount of $\tilde{W}^{\pm}$-tracks can be discovered

TRT has timing information: $\delta\beta \sim 0.1$ for $\beta < 0.85$

⇒ Wino mass may be determined: $\delta m_{\tilde{W}} \sim 10$ %

Lifetime of $\tilde{W}^{\pm}$ is insensitive to the Wino mass

$$\tau_{\tilde{W}^{\pm}}^{-1} = \frac{2G_F^2 \cos^2\theta_{\mathsf{c}} f_\pi^2}{\pi} (m_{\tilde{W}^{\pm}} - m_{\tilde{W}^0})^3 \left[1 - \frac{m_\pi^2}{(m_{\tilde{W}^{\pm}} - m_{\tilde{W}^0})^2}\right]^{1/2}$$

$\Rightarrow$ Measurement of the lifetime provides an interesting test of the Wino-LSP scenario

We should measure the travel length L of each $\tilde{W}^{\pm}$ track

[Asai, Moroi & Yanagida]

$\Rightarrow$ TRT is useful for this purpose

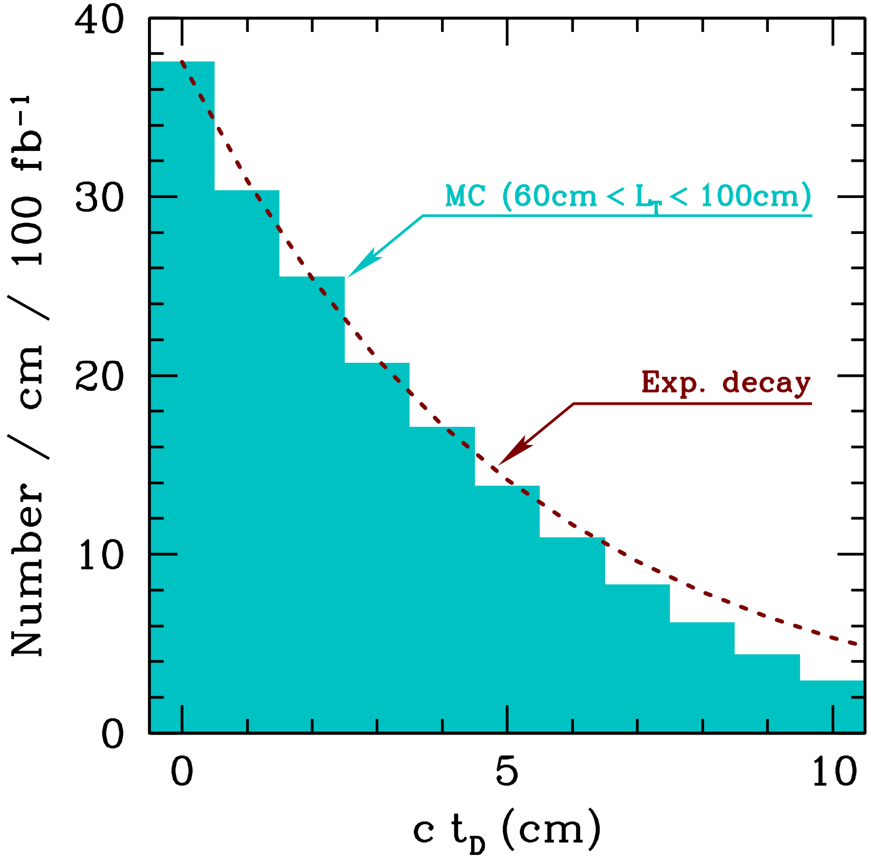
$\Rightarrow$ Momentum of each track is also available

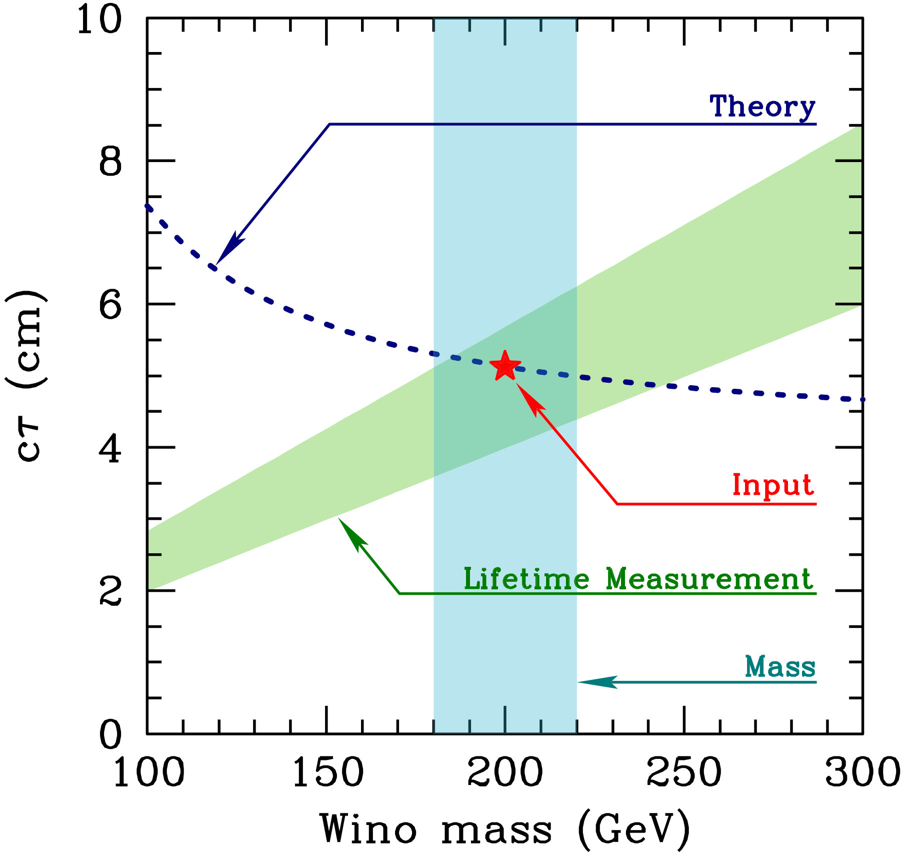
Number of charged Winos observed in the TRT

$$N_{\tilde{W}^{\pm}} \propto e^{-t_{\mathsf{D}}/\tau_{\tilde{W}^{\pm}}} \text{ with } t_{\mathsf{D}} = \frac{m_{\tilde{W}}}{|\mathbf{p}_T|}(L_T - L_T^{(\mathsf{min})})$$

Distribution of ct_D

- We use the Winos which decay in the TRT



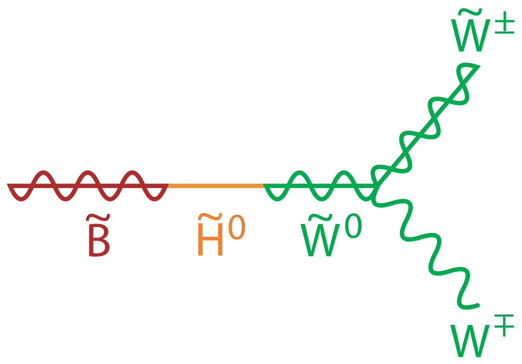


$\Rightarrow \delta\tau_{\tilde{W}^{\pm}} \sim 20\ \%$

Determination of the Bino mass

[Asai, Azuma, Jinnouchi, Moroi & Yanagida]

- The dominant decay mode of the Bino: $\tilde{B} \to \tilde{W}^{\pm} W^{\mp}$

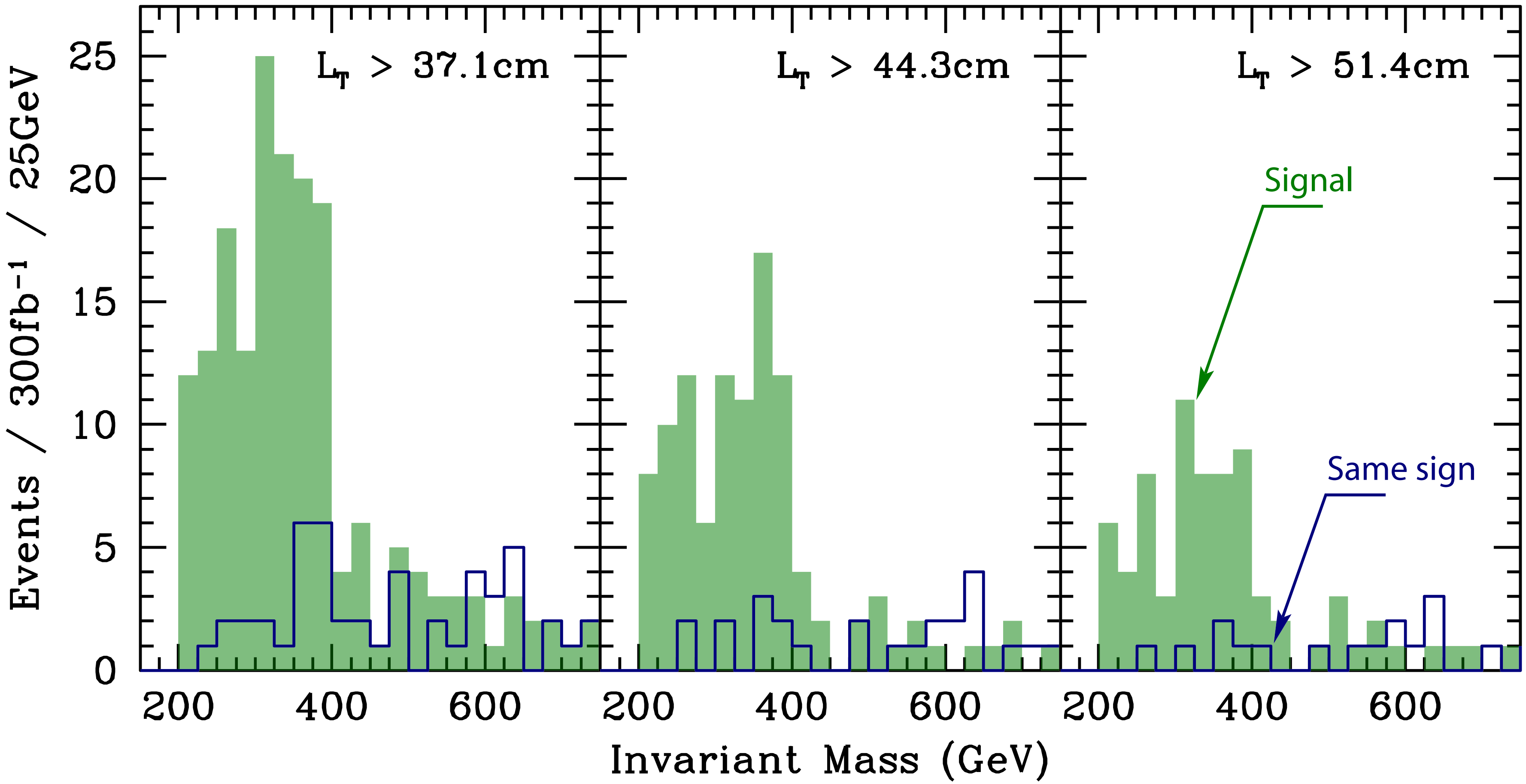


- $\tilde{W}^{\pm}$ (not $\tilde{W}^{0}$) and $W^{\mp}$ are produced by the decay

We can use the leptonic decay of $W^{\mp}$ to study $M_{\tilde{W}^{\pm} l^{\mp}}$

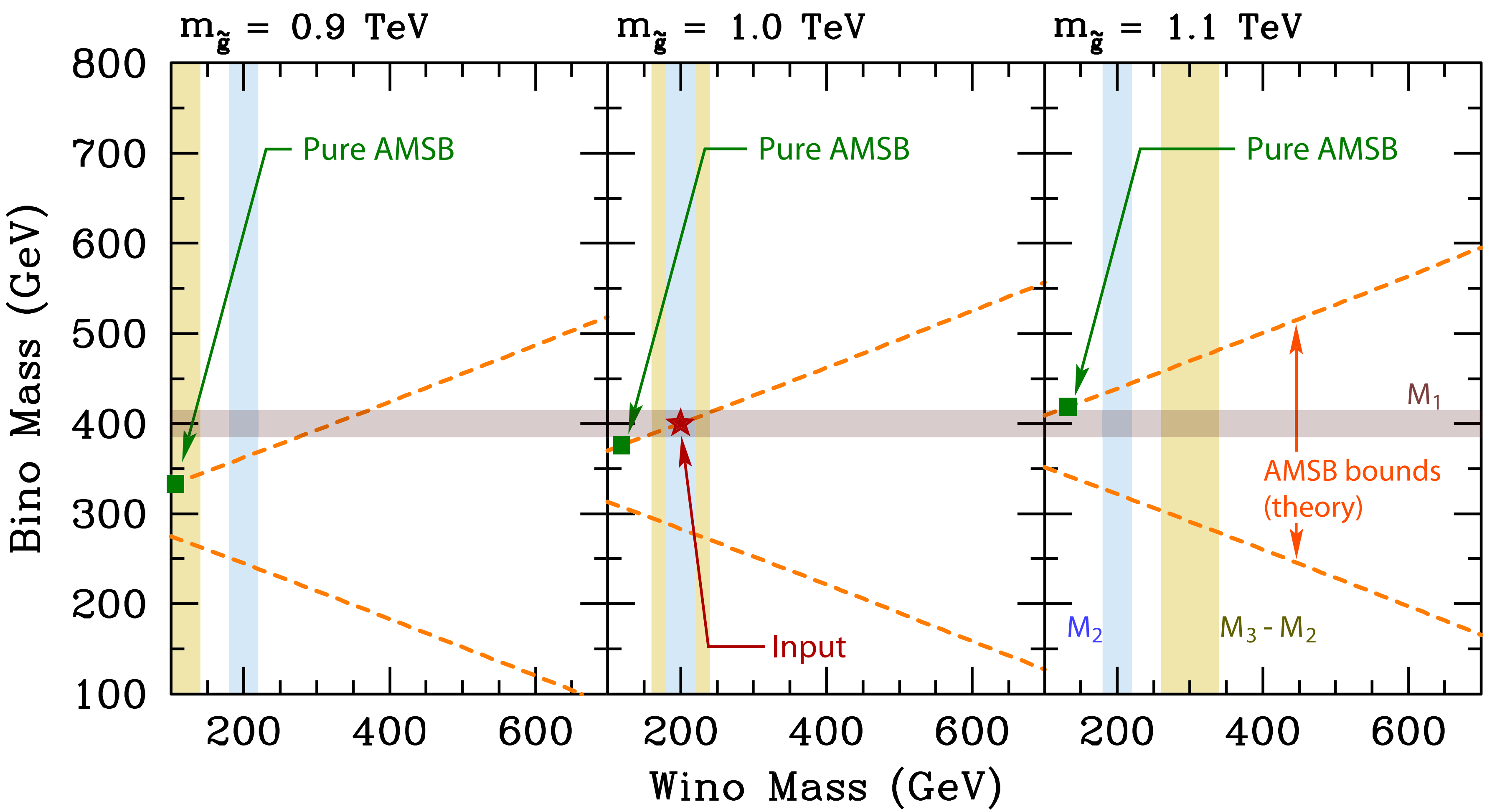
- $M^2_{\tilde{W}^{\pm} l^{\mp}} \equiv m^2_{\tilde{W}^{\pm}} + 2\left(E_{\tilde{W}^{\pm}} E_{l^{\mp}} - \mathbf{p}_{\tilde{W}^{\pm}} \mathbf{p}_{l^{\mp}}\right) \leq m_{\tilde{B}} + O(m^2_W / m_{\tilde{B}})$
- No SM background, because we identify $\tilde{W}^{\pm}$-track

Invariant mass distribution for (lepton + Wino)-system



$\Rightarrow \delta m_{\tilde{B}} \simeq 15$ GeV

Constraints on the gaugino masses



⇒ Test of the "AMSB" model is possible with the LHC

5. Summary

I have considered an exotic type of the AMSB model

- Phenomenology
- Cosmology
- LHC physics

You might think these cases are quite unlikely, but...

- There is no guarantee that the nature chooses a simple scenario (like cMSSM)

  $\Rightarrow$ We should be prepared for various "exotic" cases!

  $\Rightarrow$ I hope to see something "unexpected"

- Some of the ideas here may be applied to other models

Anyway, let's wait for results from the LHC